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TECHNICAL REPORT RH-80-3

PROPOSED NUCLEAR PUMPED LASER EXPERIMENTS UTILIZING GAMMA-RAYS

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25 February 1980

U.S. ARMY MISSILE COMMAND
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RH-80-3	2. GOVT ACCESSION NO. AD-A091 883	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PROPOSED NUCLEAR PUMPED LASER EXPERIMENTS UTILIZING GAMMA-RAYS		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dennis R. Womack Thomas G. Miller		8. CONTRACT OR GRANT NUMBER(s) 611102.H490011
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander US Army Missile Command ATTN: DRSMI-RH Redstone Arsenal, Alabama 35809		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L161102AH49
11. CONTROLLING OFFICE NAME AND ADDRESS Commander US Army Missile Command ATTN: DRSMI-RPT Redstone Arsenal, Alabama 35809		12. REPORT DATE 25 February 1980
		13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nuclear laser
Excimer laser
Photodissociation
Gamma-ray
Bleaching wave

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Two experiments are described which use a different approach to nuclear pumped lasers. Gamma-rays will be used to attempt lasing on the C→A transition in the XeF excimer. One experiment will use the gamma-rays to directly pump a high pressure laser mixture, and the other experiment will use gamma-rays to create photons which will in turn photolytically pump a XeF_2 laser mixture. Cell design is described and first-order energy deposition calculations are presented. Predicted energy outputs from half-liter laser cells are 17.0 J for the photolytic experiment, and 1.0 J for the direct gamma experiment.
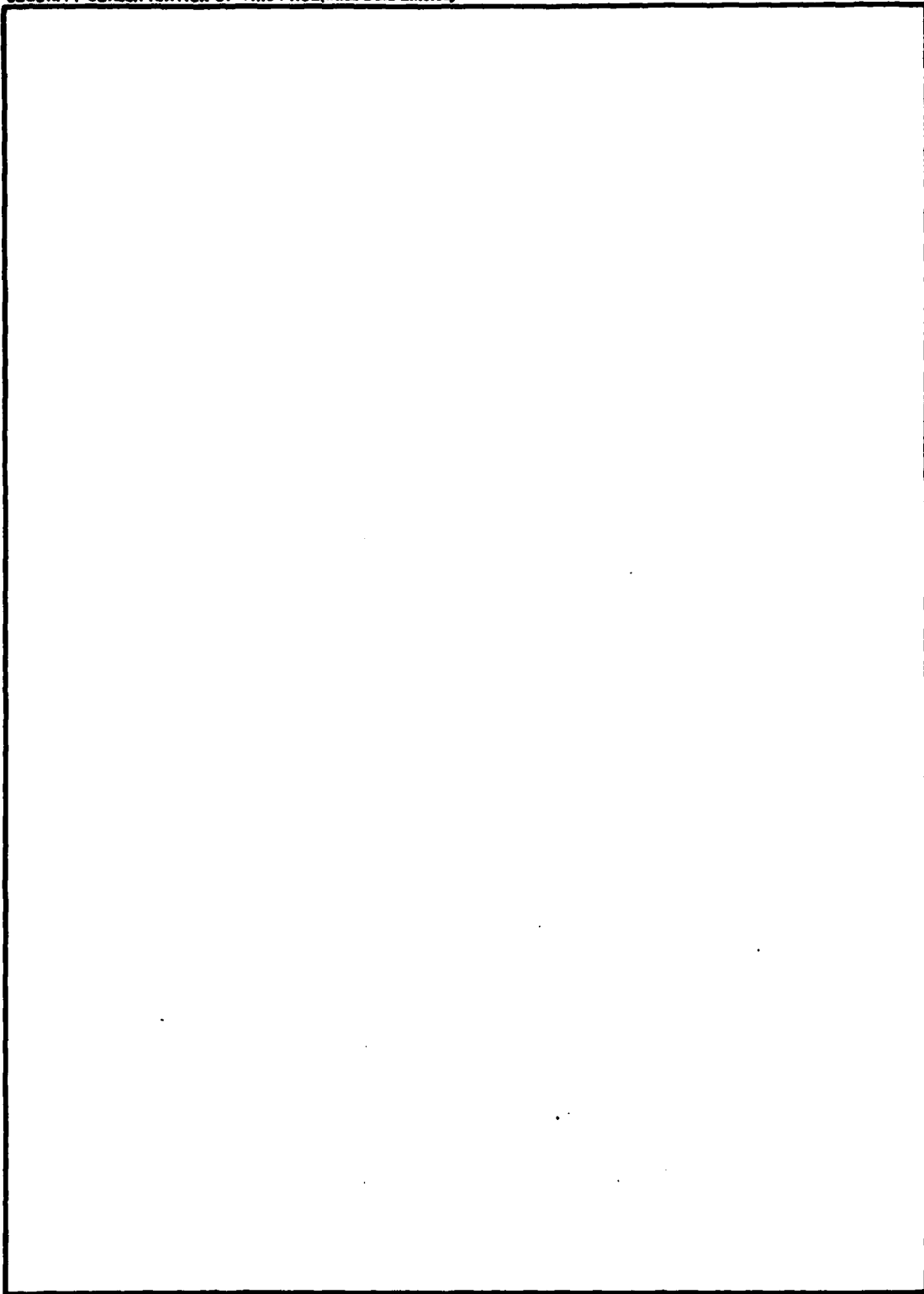
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CONTENTS

I. INTRODUCTION

A. Nuclear Pump Concept

Nuclear pumping of lasers promises to have many advantages over the traditional methods of pumping by electron beams (e-beam) or electric discharges. Simplicity of design, compactness of size, extreme energy storage density, apparent ease of scale-up and elimination of high voltage power supply technology requirements are a few of the advantages nuclear pumped lasers promise. Since 1975, about a dozen low power nuclear pumped lasers have been demonstrated, but no candidate system has moved to the forefront or demonstrated effective scaling to high powers. This paper will describe a new concept for using nuclear reactors as the pumping source for lasers; the use of gamma-rays to either directly pump a high pressure laser gas or to produce photons which in turn photolytically pump a laser gas.

The nuclear pumped lasers that have been demonstrated have used either wall coatings of boron-10 or uranium-235, or volumetric fills of helium-3. The capture of a thermal neutron results in a fission event ($^{10}B(n,\alpha)$, $^{235}U(n,ff)$, or $^{3}He(n,p)$) which results in charged particles which ionize and excite the laser gas. These methods have so far proved to be inefficient [1] means of pumping lasers even though much simpler than electrically pumped lasers. Much attention has been given to discovering methods in which gaseous UF_6 can be mixed homogeneously with laser gases in a self-critical (that is, a self-sustaining fissioning condition with no additional energy input) configuration. Large optical absorption in the VUV to near -UV and quenching by UF_6, and the steady-state or continuous wave nature of nuclear reactors has made the search for suitable laser gases unsuccessful.

The steady-state nature of nuclear reactors has perhaps been the most limiting factor of nuclear laser concepts. Promising candidate gases that can be operated at high power, continuous wave in nuclear reactors have not been discovered. Nuclear pumped lasers to date have relied upon thermal neutron capture in a fissionable nuclei. Fast burst reactors have the shortest pulse width of nuclear reactors, but the thermal neutron pulse is typically 100-150 μsec FWHM - not what one would desire in a pulsed power source. Shortening the neutron pulse and requiring repetitive pulse operation in a controlled manner are at variance with the physical nature of reactors, though some improvement can possibly be made.

Large quenching rates of UF_6, long neutron pulse
widths, and the failure of conventional laser mixtures to
operate efficiently in nuclear pumped schemes have led us to
consider a new approach to using nuclear energy for pumping
lasers. Experiments are in the design phase for the use of
gamma-rays to either directly pump high pressure laser mix-
tures or to create photons which in turn photolytically pump
a laser mixture. Gamma-rays are energetic, highly penetra-
ting radiation. The prompt gamma pulse from a fast burst
reactor is a factor of three shorter than the neutron pulse.
The penetrating nature of gamma-rays would allow large
volumes of high pressure gases to be directly pumped, with-
out introducing large populations of energetic primary elec-
trons and eliminating the need for thin foils to separate
laser gas from the pump source. The spectral energy distri-
bution can be tailored, as with electrons, and charge satu-
ration in localized regions can be avoided.

Photolytic pumping offers the potential for highly
efficient and selective excitation of lasers. Gammas
efficiently convert their energy in liquid rare gas to
UV photons. Using gamma-rays to produce photons eliminates
the need to design reactors for a large neutron leakage rate.
Recent experiments [2,3] indicate that gammas, electrons,
fission fragments and other charged particles convert 50
percent of their energy in rare gases to UV radiation. It
may be possible to homogeneously mix UF_6 and rare gases, and
convert fission energy into photons for photodissociation of
laser mixtures. Such a system would eliminate the problems
of previous concepts of self-critical lasers where the laser
gas was mixed directly with UF_6. Each fission event in U-235
releases about 190 MeV of useful energy in fission fragments,
neutrons electrons, and gammas. If 50 percent of this energy
is converted into photons (in, for example, Xe where the dimer
emits a 172 nm photon) then approximately 1.3×10^7 photons
are emitted per fission event. In a gaseous reactor
designed with a fission power density of 10^3 W/cm^3, (as in
Reference 4), approximately 9×10^{20} photons/cm^3/sec would
be created. This has tremendous potential in photolytic
systems.

B.   Laser Gas Candidate

Initial experiments in the use of gamma-rays to
pump laser mixtures will be performed with the XeF* (C→A)
excimer system. Rare gas fluoride excimers are the most
efficient visible lasers to date, and are promising

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candidates for a variety of uses from inertial fusion to communications to defense. The "normal" transition in the xenon-fluoride excimer is B→X, emitting a photon of 351 nm and having a lifetime of about 12 nsec. Recently a new transition, C→A, has been made to lase [3,5,6,7,8,9]. The C→A transition emits a photon in the visible at about 483 nm, and has a lifetime of approximately 93 nsec. A lower stimulated emission cross section, the longer lifetime, and lying about 0.08 eV below the B state makes the C state an efficient channel for excitation energy. The C state is populated predominantly by relaxation from the B state, and at high buffer gas pressures, a C/B ratio of 20 is possible [10]. Electron mixing of the two states tends to drive the populations to equilibrium, however, where the large stimulated emission cross section makes the B→X transition the favored laser action [6]. To optimize a C state laser, therefore, a pumping technique free of electrons would be ideal. Recent photolytic pumping experiments [3,8,9] have demonstrated the advantages of optical pumping.

The use of nuclear pumping with high pressure gases in the laser system XeF*(C→A) provides attractive advantages. High buffer gas pressures collisionally relax the B state to the C state, and high pressures would be required to absorb the highly penetrating gamma-rays. In Reference 10, gain was limited by the ability of the electrons to penetrate the gas. Energetic preliminary electrons are not introduced to the gas where electron mixing of the B and C states limits long pulse (>1μsec) operation with e-beams. And of course, no foils are required - the proposed experiment outlined in Section III uses a stainless steel tube as the cavity.

The photolytic experiment outlined in Section II maintains all the advantages of optical pumping but does not require the use of foils as do experiments in which an e-beam pumps a rare gas which emits photons. As in recent experiments [3,9], XeF_2 will be the laser gas (plus a buffer). The dissociation of XeF_2 into XeF* by VUV radiation at 172 nm has an efficiency close to 100 percent [3,11], and XeF_2 is optically thick to 172 nm radiation. Combined with 50 percent conversion of gamma to photon energy, such a system would have a high overall efficiency. Photolytic pumping of OCSe, which lases on the $^1S_0 \rightarrow {}^3P_1$ transition of the group VI metal Se at 489 nm, is another promising laser candidate for future investigation [12].
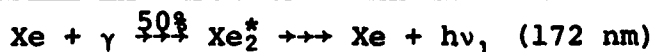
Argon has been found to be superior to other rare gases as a buffer, possibly because its higher atomic weight is better for collisionally relaxing the B to C state.

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Optical absorption by Ar is low. The relatively high atomic
weight of Ar makes it a superior choice for stopping gamma-
rays.

Section II will describe the gamma pumped photolytic
experiment. Initial experiments will be carried out with a
large flash X-ray machine where the dose rate is much higher
than with a fast burst reactor. The higher dose rate
relaxed design considerations due to geometry, reflecting
surfaces and neutron activation. Reactor experiments will
be performed at a later date. Section III describes the
direct gamma pumped experiment. Considering required
pumping rates cited in literature, the fast burst reactor is
unable to deliver the gamma dose required for lasing and so
only the X-ray machine will be utilized. Section IV presents
a summary and makes some conclusions.

II. GAMMA PUMPED PHOTOLYTIC EXPERIMENT

A schematic of the photolytic laser system is depict-
ed in **Figure 1**. A laser tube in the center is filled with
a mixture of $XeF_2/Ar/SF_6$. High pressures of Ar relax the B
to the C state, and SF_6 improves C→A performance by control-
ling the electron population. Surrounding the laser tube is
a liquid Xe cell, and the whole assembly is contained in a
stainless steel housing. Gamma-rays are absorbed in the
liquid Xe, creating 172 nm photons from the Xe_2^* dimer. The
photons pass through two suprasil walls, the inner wall of
the Xe cell and the wall of the laser tube, and into the
laser gas. The laser action is summarized as follows:

$$Xe + \gamma \xrightarrow{50\%} Xe_2^* \rightarrow\rightarrow Xe + h\nu_1 \quad (172 \text{ nm})$$

$$XeF_2 + h\nu_1 \rightarrow\rightarrow XeF^*(B) \rightarrow\rightarrow XeF^*(C)$$

$$XeF^* \xrightarrow{C-A} Xe + F + h\nu_2 \quad (483 \text{ nm})$$

A. Nominal Cell Design

The nominal cell configuration is shown in **Figure
1**. From this design calculations were performed to estab-
lish the critical dimensions of the cell. Once the dimen-
sions are determined, engineering design will follow. The
inner radius (r_i) of the liquid xenon (LXe) cell was set by
the largest diameter available of stock high grade suprasil.
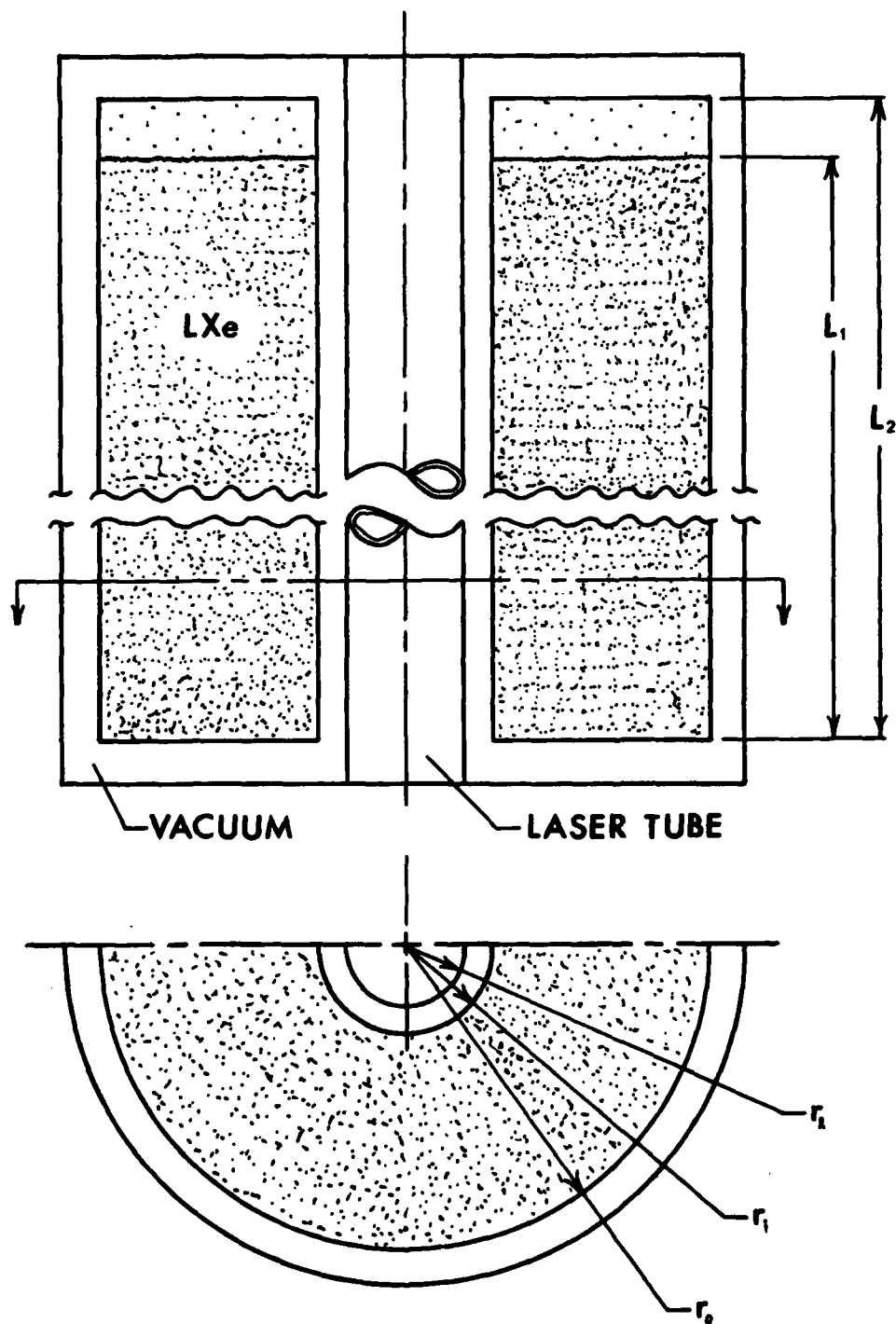This was 3.6 cm i.d. ($r_i = 1.8$).

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Figure 1.   Nominal laser cell.

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The diameter of the laser tube was chosen to be as large as possible allowing sufficient vacuum around the LXe cell. Since the heat of vaporization and boiling temperature are larger than for liquid nitrogen, no particular cryogenic problems are anticipated. Choosing a convenient stock size for the laser tube of 2.54 cm i.d. (r_ℓ = 1.27), a vacuum gap of 0.405 cm is believed to be sufficient insulation for the LXe.

The gain at 483 nm in the C$\rightarrow$A transition is low, estimated to be between 0.01 to 0.004 cm^{-1} [3,5]. Stock lengths of suprasil are easily obtainable at 100 cm, which was chosen as the length of the laser tube. The length of the LXe cell is then driven by vacuum insulation and hardware considerations. Not shown in <u>Figure 1</u> are some of the hardware considerations, such as support of the LXe cell, LXe fill lines, N_2 cooling tubes, etc. It was estimated 20 cm would be sufficient for these items, so the LXe cell length was set at 80 cm (L_2 = 80). The height of the LXe within its cell is driven by its saturation vapor, specific heat (the LXe will be absorbing a tremendous amount of energy), heat of vaporization, and the efficiency of the insulation. It is believed that if sufficient time for cooling is allowed between shots, the height of the LXe can range between 70 - 78 cm. For these calculations, 70 cm was chosen (L_1 = 70).

B. Assumptions on Efficiencies

1. Gamma$\rightarrow$Photon Conversion Efficiency

Recent experiments have demonstrated 50 percent conversion efficiencies of electrons to 172 nm photons in e-beam excitation of high pressure gaseous Xe [3,9]. Recent experiments performed in LXe at Los Alamos Scientific Laboratory (LASL) indicate that electrons, alphas, fission fragments, and gammas all convert 50 percent of their energy in rare gases into VUV photons [2]. Past experiments in liquid helium scintillation [13] indicate that lighte articles are more efficient than heavier particles i converting their energy in a volume of helium larger than the path length of the charged particle, possibly due to saturation effects in the small volume where most of the particles give up their energy. Since the penetrating ability of gammas is greater than that for electrons, it is possible that a higher conversion efficiency may be obtained. Nevertheless, 50 percent was chosen for these calculations.

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2. Transmission Through Suprasil

Manufacturer's data [14] show 70 - 75 percent transmission of 172 nm light in thin wall suprasil. Recent experiments at LASL indicate that the peak of the Xe_2^* radiation is shifted to 175 nm in LXe, which would have a transmission of 80 - 85 percent. A transmission of 70 percent was chosen for these calculations. Two suprasil tubes must be passed through to reach the laser mixture, therefore the total transmission through suprasil is taken as 49 percent.

3. Yield of XeF* from XeF$_2$

The quantum yield for production XeF* by 172 nm photolysis of XeF_2 has been estimated as unity [15]. In this report, 90 percent is used for conservatism.
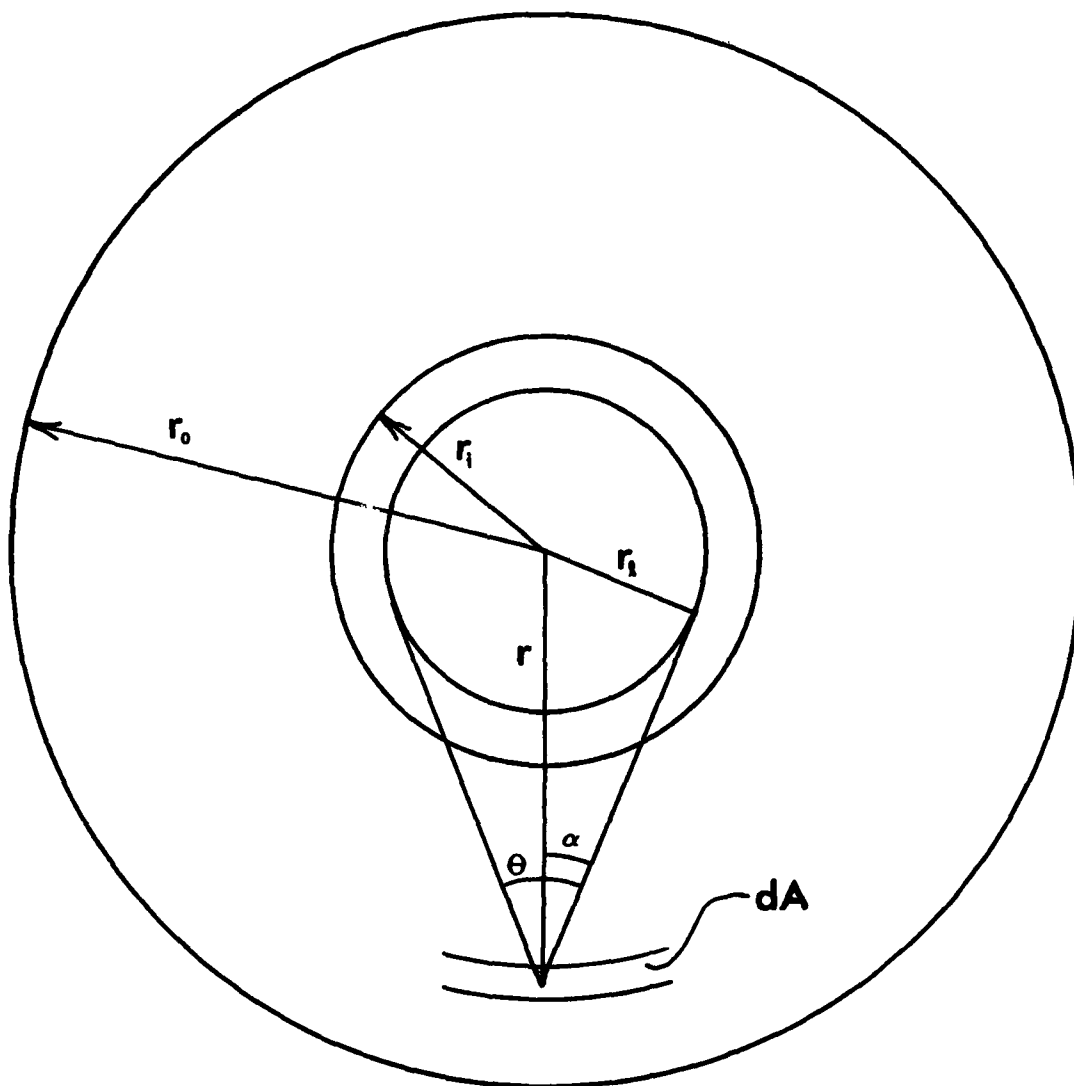
4. Geometrical View Factor

The absorption cross section of XeF_2 at 172 nm is high, the yield of XeF* is high, the transmission through suprasil is good (and may proved to be high), and the conversion of gamma energy to 172 nm photons is good. The overall efficiency of this laser cell will therefore be driven by the geometrical view factor, which is, unfortunately, poor in this experiment. Figure 2 shows the relationships used to derive the geometrical factor.

The geometrical factor was derived in 2π geometry. The probability of a photon born in the LXe intersecting the laser tube is

$$\frac{\frac{\theta}{2\pi} \cdot 2\pi r \, dr}{2\pi r \, dr}$$

where $2\pi r \, dr$ is the (normalized to a particle density of one) number of particles born in dA and $\theta/2\pi$ is the angle fraction in which a particle sees the laser tube. The total probability is then

$$G = \frac{2 \int_{r_i}^{r_o} r \sin^{-1}(r_\ell/r) dr}{\pi(r_o^2 - r_i^2)}$$

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$$G = \frac{\int \theta r \, dr}{\int 2\pi r \, dr}$$

Figure 2. Geometry factor.

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and, upon integrating,

$$
G = \frac{r_\ell^2}{\pi(r_o^2 - r_i^2)} \left[\frac{\sin^{-1}(r_\ell/r_o)}{(r_\ell/r_o)^2} + \frac{\sqrt{1-(r_\ell/r_o)^2}}{(r_\ell/r_o)} \right.
$$
$$
\left. - \frac{\sin^{-1}(r_\ell/r_i)}{(r_\ell/r_i)^2} - \frac{\sqrt{1-(r_\ell/r_i)^2}}{(r_\ell/r_i)} \right] . \tag{1}
$$

The larger r_o is in relation to r_ℓ, and the larger the dif-
ference $r_i - r_\ell$, the worse the geometrical factor. This drove
the design of the cell to liquid Xe, to confine the required
mass of Xe in as small a space as possible and to as small a
vacuum insulation gap as possible (~.405 cm).

It may be possible to place a thin shell of highly
polished Al inside the outer wall of the LXe cell, thus
increasing the geometrical view factor by reflecting a frac-
tion of the photons toward the laser tube. This will be
considered in the final design phase. A reflective shield
was not considered for these calculations.

5. Quantum Efficiency

The quantum efficiency of the reaction
$h\nu(172) + XeF_2 \rightarrow XeF^* \rightarrow h\nu(483) + Xe + F$ is $172/483 = 35.6\%$.
The laser energy to be expected will, of course, reflect a
lower efficiency.

6. Overall Efficiency

The maximum potential efficiency of this
experimental system (not considering the energy to create
the gamma-ray pump) is $(.078 \times G) \times 100\%$. If, for example,
$G = 10\%$, the overall maximum efficiency is 0.78 percent.

C. Energy Requirements

1. Energy Required to Dissociate XeF$_2$

The XeF$_2$ molecule dissociates upon inter-
action with a 172 nm photon, which has 7.2 eV of energy. A
requirement established for these calculations was that
enough energy be deposited at the peak of the photon pulse
to completely dissociate the XeF$_2$ molecules. Therefore,
twice the energy needed for dissociation was set as a
requirement so that the actual energy needed for dissociation

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is achieved over the first half of the pulse (modeled as a gaussian). The majority of the laser pumping is then accomplished in the sharply rising portion of the photon flux, terminating at the peak of the pulse. Then, the energy to dissociate the XeF_2 is

$$E_o = 2 N_D (7.2 \text{ eV/molecule}) (1.602 \times 10^{-19} \text{J/ev})$$
$$\text{joules,} \tag{2}$$

where N_D is the number of XeF_2 molecules,

$$N_D = 3.54 \times 10^{16} V_\ell P_\ell \tag{3}$$

where V_ℓ is the volume of active laser pumping, and P_ℓ is the pressure in torr of the XeF_2.

To find the energy (E_r) that must be supplied by the LXe photon source, E_o is adjusted by the various efficiencies discussed in Section III.

$$E_o = E_r \cdot \text{(yield) (transmission) (geometry factor)}$$
$$\text{(conversion)}$$

$$E_o = E_r \cdot (0.9) (0.49) (0.5) (G) \tag{4}$$

$$E_r = 4.54 E_o G^{-1} \text{ joules.}$$

2. Required Mass of LXe

The gamma dose from the two machines considered in this report was taken from open literature. The maximum dose from the AURORA flash X-ray machine at the US Army Harry Diamond Laboratory [16] and from the fast burst nuclear reactor at the US Army Aberdeen Proving Ground [17] are

$$D_A = (0.8) (5.8 \times 10^4) \text{ rads,}$$

$$D_R = (0.8) (2.2 \times 10^4) \text{ rads}$$

where A and R imply AURORA and REACTOR, the 0.8 is an estimated gamma attenuation in the walls of the laser cell, and dose in rads was adjusted for LXe from values given in silicon. There are 100 rads in a joule per kilogram, therefore

$$D_A = 464 \text{ J/Kg,} \tag{5}$$

$$D_R = 176 \text{ J/Kg.} \tag{6}$$

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With Equations (4) and (5) or (6), the mass of liquid xenon can be determined,

$$m = \frac{E_r}{D} \text{ Kg,}$$

and the volume of LXe can be found,

$$V_1 = \frac{(1000)m}{\rho} = 324.25 \; E_r D^{-1} \quad cm^3, \tag{7}$$

where the density of LXe is 3.084 g/cc.

3. Laser Cell Dimensions

Combining Equations (1), (2), (3), (4) and (7), a relationship between the laser tube radius (r_ℓ), inner LXe cell radius (r_i) and the outer LXe cell radius (r_o) can be found.

$$V_1 = \pi L_1 (r_o^2 - r_i^2) = \frac{(324.25)\;(4.54)\;E_o}{DG}$$

where L_1 is the height of the liquid Xe.

$$\pi L_1 (r_o^2 - r_i^2) = (1472.1)(0.08167)\;\frac{V_\ell P_\ell}{DG}$$
$$= (120.226)\;\frac{\pi L_2 r_\ell^2 P_\ell}{DG}$$

where L_2 is the length of actively pumped XeF_2 (see Section II). Using the dose from AURORA,

$$L_1 r_o^2 = L_1 r_i^2 + (0.259) L_2 P_\ell r_\ell^2 G_\ell^{-1} \; .$$

The inner LXe cell radius was described in Section II as being equal to the laser tube radius, plus laser wall thickness, plus vacuum gap (a), and (including the wall thickness in a)

$$r_i = r_\ell + a$$

$$r_o^2 = r_\ell^2 \left[1 + (0.259)\;\frac{L_2}{L_1}\;\frac{P_\ell}{G} \right] + 2a r_\ell + a^2 \tag{8}$$

A similar equation can be found for the dose at the fast burst reactor,

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TABLE 1. ENERGY DEPOSITION AND CONTENT

MASS LXe = 24.3 Kg
MAX PHOTON ENERGY FROM AURORA = 11,275 J
MAX PHOTON ENERGY FROM REACTOR = 4,277 J

XeF$_2$ PRES (TORR)	E TO DISSOCIATE XeF$_2$ (J)	E DEPOSITION REQUIRED IN LXe (J)	% OF XeF$_2$ DISSOCIATED AT PEAK	MAX THEORETICAL OUTPUT AT 483 nm (J)
AURORA				
2	66.2	2822	400%	11.8
4	132.4	5644.1	200%	23.6
6	198.6	8466.1	133%	35.4
8	264.9	11292.5	99%	47.2
REACTOR				
2	66.2	2822	152%	11.8
4	132.4	5644.1	76%	17.9 (?)
6	198.6	8466.1	51%	?
8	264.9	11292.5	38%	?

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$$r_o^2 = r_\ell^2 \left[1 + (0.683)\, \frac{L_2}{L_1} \frac{P_\ell}{G} \right] + 2ar_\ell + a^2 \qquad (8')$$

Knowing the nominal design heights, L_1 and L_2, from Section II, and having set the radii r_ℓ and r_i from economic reasons, one only needs to determine the pressure of XeF_2 desired, and then iterate between Equations (8) and (1) to find the required radius of r_o.

The vapor pressure of XeF_2 at room temperature is 4 torr, and the majority of laser experiments have thus far utilized this pressure. It would be desirable to conduct experiments up to twice the room temperature vapor pressure to investigate the bleaching effect* in the photolysis of the XeF_2. Choosing 8 torr pressure, and using $L_2 = 80$ cm, $L_1 = 70$ cm and $a = 0.405$ from Section II, by iterating between Equations (8) and (1) one gets $r_o = 6.3$. In the interest of design, LXe costs, absence of consideration of a reflector, and in light of the fact that over twice the energy required for dissociation is being deposited in the cell, a dimension for the outer radius of the LXe cell was chosen to be $r_o = 6$ cm, and then $G = 10.7$ percent.

4. Energy Deposition

With the laser tube and LXe cell dimensions, rough estimates on energy deposition and content can be made. With the geometry factor set, the only variables in Equations (2) through (7) are the XeF_2 pressure and the dose. Table 1 summarizes energy deposition and content over a range of pressures and for the dose available at the AURORA facility and the fast burst reactor facility. The volume of LXe was set when r_o was chosen, which in turn was chosen by pressure and energy requirements. The mass of LXe is then 24.3 Kg, therefore the maximum energy deposited in the LXe is 11.3 KJ and 4.3 KJ, from AURORA and the reactor respectively. The second column of Table 1 gives the total energy deposition required to dissociate the XeF_2 at the peak of the pump pulse (which, as mentioned in Section C.1, is twice the actual required energy). The third column gives the required deposition of gamma energy in order to achieve the requirements of the second column. The fourth column is the ratio of the available gamma energy to what is required. In the cases where greater than 100 percent of the energy is available, the experimental cell can be moved further away from the gamma source, thus reducing the dose. The last column is the maximum theoretical laser output at 483 nm,

*See Author's Note in Appendix A.

merely considering the quantum efficiency. The real output
will, of course, be lower and can only be determined from
experiment or from a laser kinetics computer code. A
kinetics code for photolysis of XeF_2 and subsequent lasing
on the C→A transition of XeF* is being developed by Dr. E.
Fisher and colleagues at Wayne State University under the
sponsorship of the Ballistic Missile Defense Advanced Tech-
nology Center.

D. Laser Potential

For the cell described in this report, and at 4
torr of pressure of XeF_2, preliminary laser kinetic calcula-
tions by Fisher, et al.** (for AURORA), have been performed.
The calculations indicate a laser output energy of 21 J,
peak power of 135 MW. This is orders of magnitude greater
than any previous experiments where an e-beam is used to
create the Xe pump photons [3,5].

Initial experiments will be performed at the AURORA
facility. The factor of three greater dose than that of the
reactor and the short pulse length are much more favorable
to lasing in an attempt to prove gamma-rays can be used to
pump excimer lasers.

Since the pulse width and rise time at the reactor is
relatively long, lasing cannot be confidently predicted.
Initial kinetics calculations by Fisher, et al.,** indicate
lasing may be possible at 4 torr. The phenomena of the
bleaching wave effect will play an important role in long
pulse systems. The slow rising initial gamma pulse must be
kept out of the gain region until the pump intensity reaches
its maximum. By forcing the pump to bleach its way into the
gain region, such a delay may be possible.

III.   DIRECT GAMMA PUMPED EXPERIMENT

A. Cell Design

The proposed cell for the direct gamma pumping
experiment is nothing more than a stainless steel tube, one
inch inner diameter, with flanges on each end to accommodate
the optical assembly which will also be used on the photoly-
sis cell. The gas mixture will be Ar/Xe/NF_3 with 2-10 Torr
of Xe, 2-25 Torr of NF_3, and 10-25 atm of Ar. Previously
stated in Section I, high buffer gas pressures are required
to effectively relax the B state to the C state. Electric
discharges are not suitable at these high pressures, and

**See Author's Note in Appendix A.

e-beams have limited volume scaling at these pressures. The experiment described in [10] found that peak gain of the C→A transition increased linearly with Ar pressure up to 20 atm, where the e-beam suffered from reduced penetration. Electron mixing is not eliminated in this concept as it is with photo-lytic pumping because the gamma-rays slow down and are absorbed predominantly by compton scattering, which produces secondary electrons. Energetic primary electrons, however, are not introduced into the laser mixture. How important an advantage this is remains to be determined.

B. Pumping Density

A pumping rate of 100 J/(ℓ-μs) is quoted as an efficient power density for typical rare gas fluoride laser operation [18]. This power density will dictate the pressure requirements of the buffer. Argon is heavier than silicon, so the dose in silicon will yield a conservative calculation. At the AURORA facility the maximum dose is 4.5×10^4 rads (Si). The FWHM is 0.15 μs, therefore a desired energy density over the total pulse is 15 J/ℓ. Thus, the density of gas can be found (ρ)

$$\rho = \frac{(15 \text{ J}/\ell)(1000 \text{ g/Kg})}{(4.5 \times 10^4 \text{rads})(0.01 \text{ J/Kg-rad})} = 33.3 \text{ g}/\ell \text{ .}$$

To achieve a power density of 100 J/(ℓ-μs) a pressure of AR buffer of 20.1 atm is required in our half-liter laser cell. Where the useful limit of operation of e-beams is below 20 atm, the gammas "have yet begun to excite."

The long pulse width at the reactor (50 μsec) would require an energy density of 5000 J/ℓ over the pulse. The dose at the reactor is not great enough to achieve this input.

Initial plans are to investigate buffer pressures up to 25 atm. Even greater pressures will be utilized, depending on cell limitations, if time permits. The kinetics of the experiment have not been developed, but typically 5 percent efficiency is realized (energy deposited in laser/laser energy out).

C. Laser Potential

For a laser cell utilizing between 20-40 atm of Ar buffer, an energy density at AURORA of 15-30 J/ℓ will be achieved. This experiment will utilize a half liter cell. Thus, an output energy of 0.7 - 1.5 joules may be possible. If direct gamma pumping of the XeF*(C→A) proves to be a

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desirable method of pumping, an intense gamma source must be found. We recognize that the AURORA machine is monstrous in size. It was designed to give a large gamma dose to an extremely large volume. Smaller e-beam devices may however, be able to create a sufficient gamma (X-ray) dose to a laser volume and eliminate the need for foils and make possible the use of high pressures. Also, methods do exist for increasing the gamma dose from pulsed reactors, although the dose rate may be a severe problem to overcome. The possibility of extremely high pressure lasers (with much reduced e-beam induced shock and acoustic effects) is a concept that has received little attention due to past difficulties.

IV.   CONCLUSIONS

Simple experiments have been devised to prove the feasibility of using gamma-rays as the prime pump in XeF excimer lasers. The penetrating ability of gammas, efficient conversion of gamma to photon energy, and the kinetic simplicity of optical pumping promise to yield compact, high power excimer laser systems.

Since a nuclear reactor has not yet been constructed specifically for laser experiments, and since current fast burst reactors are marginal pump sources for laser systems, initial proof-of-concept will be performed at the AURORA flash X-ray facility. Utilizing a machine like the AURORA to create gamma-rays is grossly inefficient from wallplug to laser output. Should gamma pumping of lasers prove attractive and desirable, attention must be paid to designing nuclear reactor concepts that are suitable and efficient for nuclear lasers.

Nuclear energy is the most compact energy source known; one pound of uranium-235 holds about 3×10^{12} joules of energy [19]. This advantage is nullified by poor efficiency; about 90 percent of the energy is in fission fragments, which are typically lost in walls or reactor fuel. The full advantage of nuclear pumping cannot be realized unless one of the following happens:

- A laser mixture evolves that can be mixed homogeneously with reactor fuel
- An optical pumping medium can be mixed homogeneously with fuel or
- A method can be found to convert a major portion of fission energy into gammas or neutrons.

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On the other hand, poor efficiency may be tolerable if suffi-
cient energy can be extracted in the form of laser light
since a nuclear reactor can be very compact and operate for
years without refueling. In addition, power can be tapped
from the reactor in a traditional manner to supply the elec-
trical needs of a total laser system station.

APPENDIX A

KINETIC ANALYSIS OF PHOTOLYTIC EXPERIMENTS

by

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AUTHOR'S NOTE - The following material was lifted directly from a letter report entitled "Analysis of University of Florida Experiment". R. Walters and others at the University of Florida are pursuing experiments where thermal neutrons are captured by helium-3, which fissions, excites and ionizes gaseous Xe. The Xe dimer produced emits a 172 nm photon which optically pumps a $XeF_2/N_2/SF_6$ mixture. A preliminary look at the gamma pumping experiments proposed in this report was included in the letter report by Lim and Fisher. A detailed report is to follow.

We have carried out detailed laser model calculations in support of the proposed experiments by the University of Florida. The conclusions from these calculations are summarized here. Of main importance is the optimum partial pressure of XeF_2 and the optimum reflectivity of the output mirror for the cavity configuration contained in the latest Florida report. Lasing is predicted in the Florida experiment with optimum conditions being 7 torr XeF with an output mirror reflectivity of 98 percent. Under these conditions, a maximum power of nearly 30 kwatts is predicted at about 100 μsec. The output is found to seriously degrade under lower output reflectivity conditions. Laser energy extracted is predicted to be about 12 joule/liter at 480 nm for about 130 joule/liter 172 nm photons absorbed. Total energy input to the Xe pump is taken to be 230 joule/liter making the overall efficiency 5.2 percent. This low efficiency results from both the long pulse width of the proposed reactor and the relatively low intensity of the pump source.

Finally, preliminary calculations are presented on the AURORA and APG reactors as proposed by G. Miller. The results of these calculations are optimistic but bleaching wave effects complicate the analysis. Preliminary results are also included on the properties of bleaching waves in higher pressure YeF_2 configurations.

Preliminary Calculations on the APG and AURORA Reactors

The major problem associated with the Florida experiment is the direct contrast between the fast laser kinetics and the slowly rising reactor pulse. As the absorbing media is pumped by a slowly rising pump, the excitation is rapidly degraded due to spontaneous emission and quenching processes. If the photon flux is minimal, as in the Florida experiment, direct quenching of the laser excited states is caused by undissociated XeF_2. A faster rising pump reactor with higher maximum photon flux would remedy these objections. The APG reactor is a slight improvement while the AURORA facility completely satisfies these points. We here offer preliminary calculations on these two systems.

APG Reactor

The beam flux assumed in these preliminary calculations is $2.8 \times 10^{21} \exp(-(t-5.0 \times 10^{-5})^2/9.02 \times 10^{-10})$ photons/cm^2-sec which represents an incident energy flux of 169 joules/liter. Two calculations on a 10/760/4 torr mixture of $SF_6/N_2/XeF_2$ are shown in Figures A1 and A2 for laser on conditions. Although the maximum beam current is about the same as the Florida experiments the pulse width is smaller

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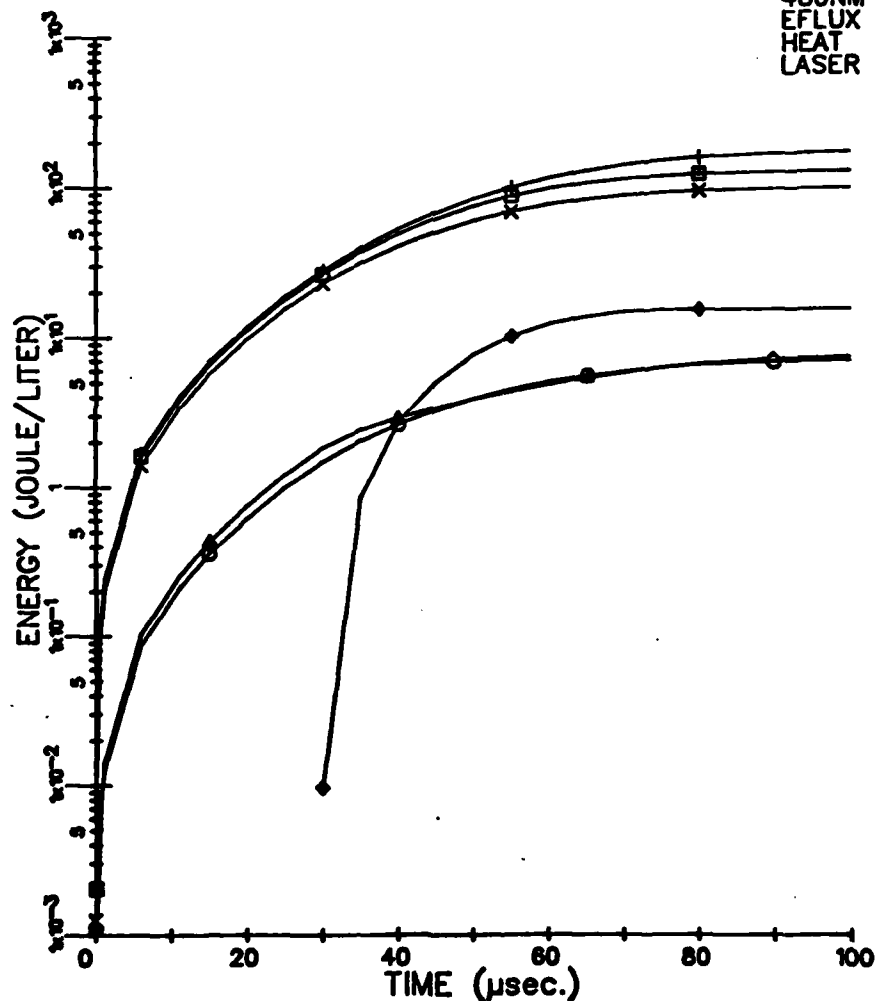Figure Al.   Power output at reactor.

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Figure A2.   Specific energy output at reactor.

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leading to increased excitation. Under lasing conditions with output mirror of reflectivity 98% and including an intrinsic loss of 10^{-5}/cm, strong lasing is predicted as shown in Figures A1 and A2. Peak power for the listed conditions is 200 kW at 50 μsec with laser energy output of 15 joules/liter and energy absorbed of 126 joules/liter.

AURORA Reactor

The AURORA facility features both greatly increased maximum beam flux and also greatly reduced beam width. These changes produce a much closer match between the pump source and the time scales of the chemistry. The incident beam flux for this case is assumed to be 2.4×10^{24} exp($-(t-1.5 \times 10^{-7})^2/8.1 \times 10^{-15}$) with an energy of 445 joules/liter. With this greatly increased beam flux, the XeF_2 is bleached out quite early in the pulse. The excited state densities are very high. Lasing behavior is shown for the case of 90 percent output mirror in Figures A3 and A4. The predicted output is impressive, showing 149 joules/liter energy absorbed and 42 joules/liter laser output for 28 percent efficiency. The peak power is calculated to be 135 Mwatts at 130 nsec.

Although the predicted output from the AURORA experiment is high, we must caution that spatial effects due to a bleaching wave phenomena implicate these calculations and may lead to altered results. We have formulated the equations necessary to characterize the bleaching wave including a spatial and temporal prediction of excited state densities. The complication arising from a bleaching wave not only effects the spatial coherence of the laser medium through local temperature and pressure increases but the total medium gain through the fact that parallel optical mirrors must be used to capitalize on the annular excitation induced by the bleaching wave. A preliminary presentation of the bleaching wave phenomena in XeF_2 is presented in the following section.

Photolytic pumping is clearly an effective way of exciting NP gas lasers since a large volume of gas medium can be excited over various spectral regions. However, if the pressure of the absorbing gas is high or the length of the absorption cell is enlarged in order to increase the laser power, the absorption process can behave like a bleaching wave.

In the photolysis of XeF_2 with 172 nm photons in a coaxial cylinder, bleaching waves can occur if $R \gg 1/N\sigma$, where N is the number density of XeF_2, σ is the absorption cross section, and R is the radius of the XeF_2 laser cell. The

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Figure A3.   Power output at AURORA.

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XEF2 LASER KINETICS EVALUATION
ENERGY VS TIME
RIES/WSU FEB., 1980

FWHM=150 nsec GAUSSIAN BEAM, WITH MAX. 2.4E+24 BEAM CURRENT AT 150 nsec
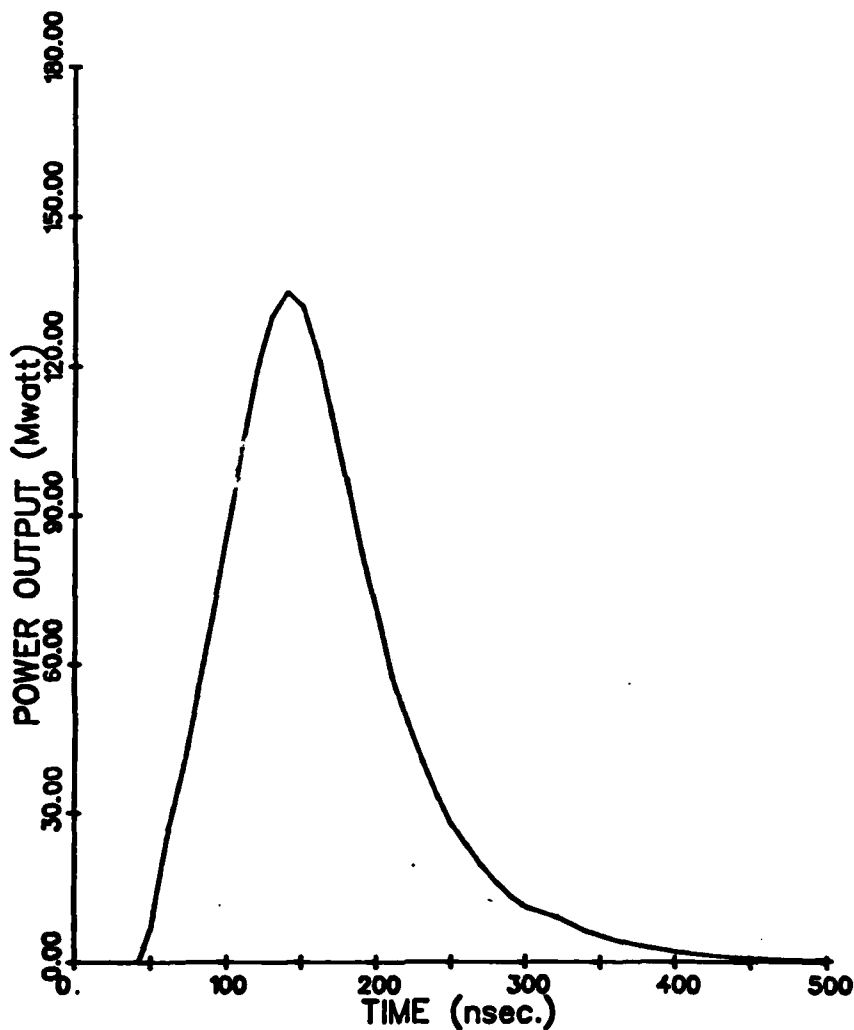N2: 760 TORR   SF6: 10 TORR   XEF2: 4 TORR   LASER ON R=0.90 L=.0001

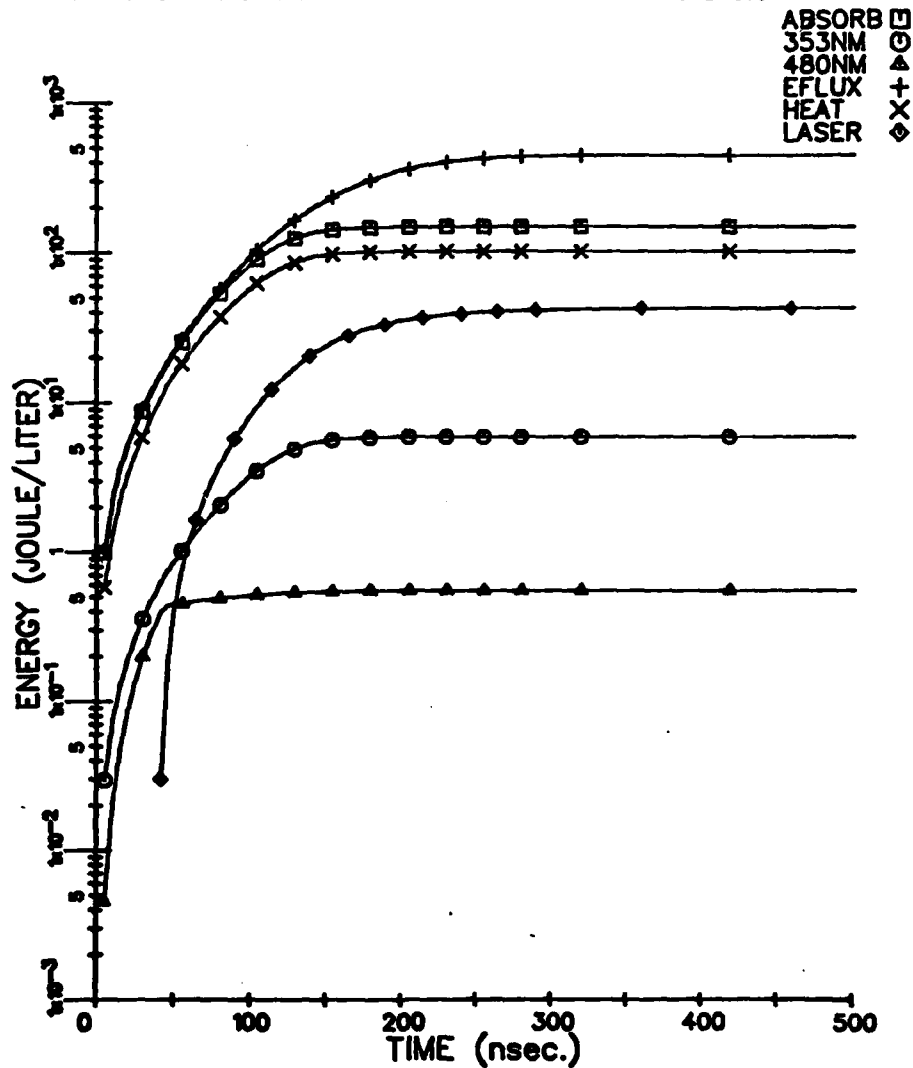ABSORB ⊟
353NM ⊕
480NM ▲
EFLUX +
HEAT ✕
LASER ◆

Figure A4.   Specific energy output at AURORA.

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well known Beer-Lambert's law, $dI = -N\sigma I dr$, describes the absorption process of the changing intensity with position. The photon intensity and the number density of the absorbing gas is a function of position and time in an optically thick medium. The following two transport equations describe the bleaching wave phenomena in cylindrical geometry (neglecting diffusion).

$$\frac{\partial N}{\partial t} = -\sigma NI$$

and

$$\frac{1}{c}\frac{\partial I}{\partial t} = \frac{1}{r}\frac{\partial(rI)}{\partial r} - \sigma NI$$

where, I = photon flux (photon/cm^{2}sec)
and N = absorbing gas density (molecules/cm^3).

The above two coupled partial differential equations have been solved using a Runge-Kutta integration scheme subject to a gaussian beam flux of $2.656 \times 10^{24} \exp(-(t-2.0\times10^{-7})^2/1.44\times10^{-14})$ with 20 torr of XeF_2. The change of the XeF_2 number density at various radial positions with respect to time is shown in <u>Figure A5</u>. This figure shows that substantial pulse sharpening has occurred near the center of the cylinder. The velocity of the bleaching wave can be estimated from the balance of the number density and photon flux. For a rectangular geometry this wave velocity, V, is $V = I/N$, and in cylindrical geometry is, $V = RI/Nr$. The results indicate an acceleration effect due to the Gaussian beam shape with increasing photon flux up to 200 nsec. Near the center, an additional acceleration occurs as a result of the cylindrical geometry factor of R/r. The example chosen above has bleached out at about 220 nsec which is just past the peak of the input pulse.

The bleaching wave phenomena in high flux-high partial pressure XeF_2 has been shown to induce substantial pulse sharpening as wave propagation proceeds into the medium. This results due to the absorption of the more slowly rising components of the pump pulse in the outer regions of the medium leaving the higher intensity part of the pump pulse to be incident on the innermost regions of the medium. Since pulse sharpening tends to drive the time scales of the incident photon flux toward the time scales associated with the fast chemistry of the XeF_2 system, greater excitation is predicted near the center of the medium. This greater excitation is in part compensated by spatial inhomogeneities and

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local thermal and pressure effects. The collective effect is under continued investigation.
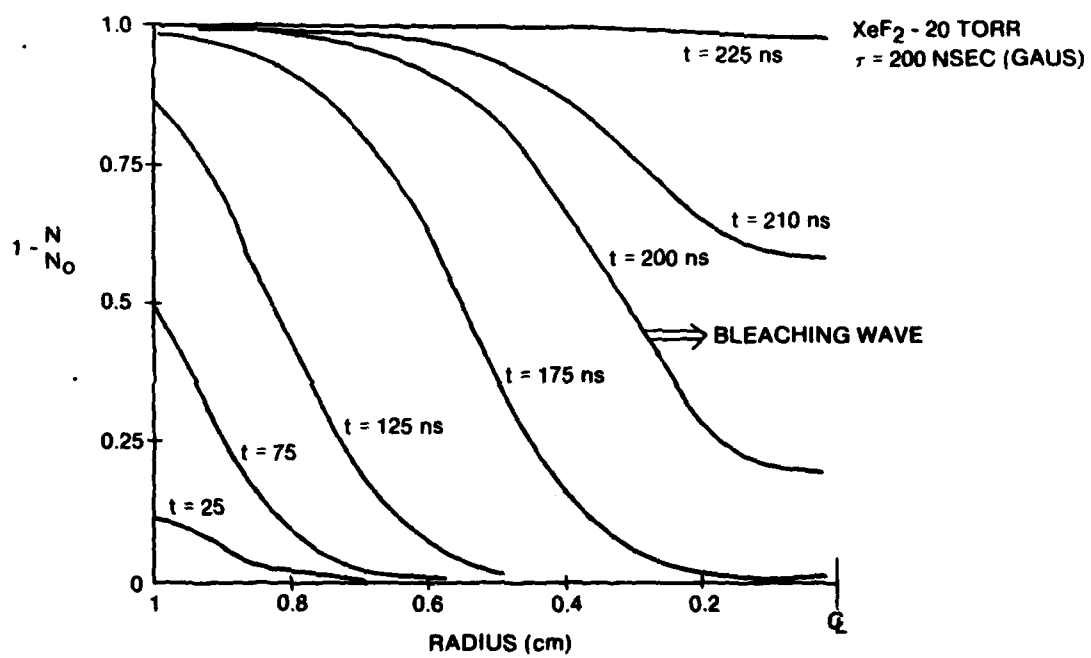

Figure A5.   Bleaching wave effect.

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